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Definitions of Attributes for Limb-Scanning or Limb-Imaging Remote Sensing Systems

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13. ABSTRACT *(Maximum 200 words)*

This document presents definitions of parameters related to observations of the upper atmosphere by ultraviolet remote sensing systems which image or scan the limb of the earth. These parameters or "attributes" form the basis for organizing databases and accessing data through database management systems. The emphasis here is on attributes that characterize the attitude and ephemeris of the platform carrying the instruments as data are gathered. The presentation covers various coordinate systems and provides mathematical formulas for geometric parameters related to limb-scanning systems.

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LIST OF ABBREVIATIONS

ARGOS	Advanced Research and Global Observation Satellite
BDC	Backgrounds Data Center
DBMS	Database Management System
DEC	Declination
DGRF	Definitive Geomagnetic Reference Field
DMSP	Defense Meteorological Satellite Program
DPF	Data Processing Facility
EUV	Extreme Ultraviolet
FUV	Far Ultraviolet
GAC	Global Area Coverage
GEI	Geocentric-Equatorial Inertial Coordinate System
GEI J2000	Geocentric-Equatorial Inertial Coordinate System of the year 2000
GEO	Geocentric Coordinate System
GHR	General Housekeeping Record
HIRAAS	High Resolution Airglow/Aurora Spectroscopy
IGRF	International Geomagnetic Reference Field
MAG	Geomagnetic Coordinate System
MUV	Middle Ultraviolet
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NUV	Near Ultraviolet
RA	Right Ascension
RAIDS	Remote Atmospheric and Ionospheric Detection System
RDBMS	Relational Database Management System
SEZ	Horizon Coordinate System ("South, East, and Zenith")
SF	Satellite-Fixed Coordinate System
SGR	Satellite Geodetic-Reference Coordinate System
SSULI	Special Sensor Ultraviolet Limb-Imager
TIROS	Television Infrared Observation Satellite
USAF	United States Air Force

DEFINITIONS OF ATTRIBUTES FOR LIMB-SCANNING OR LIMB-IMAGING REMOTE SENSING SYSTEMS

1. INTRODUCTION

This document contains descriptions of the attributes, or metadata, to be used to access data produced by limb-scanning or limb-imaging remote sensing systems. While this document is specific to the Remote Atmospheric and Ionospheric Detection System (RAIDS)[1,2], the types and descriptions of attributes and the mathematical formulas governing them are general. Thus the document should be useful for subsequent limb-scanning missions, some of which will be discussed below. The attributes are inputs to a detailed or "program" catalog for a relational database management system (RDBMS) designed by the Naval Research Laboratory (NRL) Backgrounds Data Center (BDC). A program catalog consists of tables of parameters describing each scan and is the basis for queries of the system by the user. The present catalog contains a "scans data table" and a "mode data table," the union of which specifies the characteristics of a particular platform scan or instrument wavelength scan, corresponding to a given mode of instrument activity. The attributes described herein are entries to the scans and modes data tables.

The immediate application of the catalog is to the storage and access of data produced by RAIDS. RAIDS consists of eight instruments which provide spectral intensities within the ultraviolet, near-infrared, and visible wavelength ranges and covers a tangent altitude range of 50-750 km. This will permit RAIDS to measure global distributions of the major neutral and ionized species and important minor constituents within the thermosphere and the ionosphere. The mission will nominally last for three years. The host platform was to be a National Oceanic and Atmospheric Administration (NOAA) Television Infrared Observation Satellite (TIROS-N series weather satellite)[3]. Although the unfortunate loss of the NOAA-13 satellite in August of 1993 has precluded that possibility, we anticipate that RAIDS will ride aboard a satellite with a similar design and orbital parameters. As a result, this document will remain current.

A number of other limb-scanning systems which are similar to RAIDS in both capability and deployment will begin flying in calendar year 1996. Each will again have a nominal lifetime of three years and, at a minimum, will cover a significant portion of the extreme ultraviolet (EUV) and far ultraviolet (FUV) wavelength ranges covered by RAIDS. The Advanced Research and Global Observation Satellite (ARGOS) will fly in mid 1996. The ARGOS mission is scientific in nature, including not only limb-scanning measurements comparable to RAIDS at EUV, FUV, and MUV (middle ultraviolet) wavelengths but also the High Resolution Airglow/Aurora Spectroscopy (HIRAAS) system with much higher resolution than RAIDS, plus limb-imaging systems, as well. Beginning as early as 1997, a sequence of United States Air Force (USAF) Defense Meteorological Satellite Program (DMSP) missions will fly, lasting well past the year 2010. The Special Sensor Ultraviolet Limb-Imager (SSULI) aboard each DMSP satellite will provide the spectral data necessary for the near-real-time assessment of the state of the thermosphere and ionosphere. The RAIDS, ARGOS, and SSULI missions and their anticipated follow-ons will also provide a consistent long-term data set with which to determine signatures of global change.

The generation of attributes occurs when raw data ("Level 0 data") arrive from the satellite data

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processing activity. The Level 0 data include satellite attitude, ephemeris, and health data and scientific instrument data. In the case of the NOAA TIROS-N satellite, for example, transmission of the RAIDS Level 0 data to ground processing activities would occur as part of the global area coverage (GAC) data stream[4]. The ground activities would then decommutate the data, extracting the data relevant to RAIDS, creating Level 0 data files of a specific format, and transmitting the files to NRL over Internet. We assume that the formatting conventions used by NOAA[4] will hold for the actual data handling activity: the level 0 data file consists of blocks of several records. The first record of a block is the "General Housekeeping Record" which contains all satellite related data. The remaining records in the block contain scientific instrument health and observations.

The RAIDS Data Processing Facility (DPF) converts the raw compressed Level 0 data to the archival Level 1 format in several steps. The Level 1 data set constitutes the primary archive and consists of expanded, uncalibrated data. The DPF software first expands the 705 byte GAC record into 844 byte records and breaks the NOAA files into orbit size files. Next the software calculates the program catalog attribute information and performs instrument health checks. The attribute information is then given to the database system operator for insertion into the Database Management System (DBMS).

The following coordinate systems are used in various attribute calculations and are described in Appendix A:

(1) Geocentric-Equatorial Inertial Coordinate System of the Year 2000 (GEI J2000),
(2) Geographic Coordinate System (GEO),
(3) Horizon Coordinate System ("South, East, and Zenith" (SEZ)),
(4) Satellite-Fixed Coordinate System (SF),
(5) Satellite Geodetic-Reference Coordinate System (SGR),
(6) Geomagnetic Coordinate System (MAG).

The convention used to format this document is illustrated in Figure 1. Definitions are followed by an example, diagram, or equation only when necessary for clarification. All italicized words are defined in the glossary in Appendix B. The equations and algorithms for computing various attributes are in Appendix C. Coordinate transformations from GEI to GEO and GEO to MAG are in Appendix D.

RDBMS TABLE NAME

Attribute Name

A short Description.

Type:	C, FORTRAN, IDL
Example:	An example is not given for every attribute.
Figure:	A diagram is not given for every attribute.
Equation:	An equation is not given for every attribute.

Figure. 1 - Document format

2. SCANS DATA TABLE

2.1 Orbit File Name

An array of 11 characters which contains the name of the orbit file. This name does not include device names or subdirectories. The first two characters identify the database that the file belongs to. For RAIDS this will always be "ra" to show that this file belongs to the RAIDS Database. The next six characters contain the orbit number. The last four characters will always be ".orb" because this is an orbit file.

Type:	unsigned char[11], CHARACTER*11, String.
Example:	ra00101.orb is the name of the 101st orbit file.

2.2 Beginning Record Byte Number

A number representing the byte offset from the beginning of the orbit file to the byte at which the first record for the current scan data begins. The first byte of the file is considered to be byte zero. This follows the standard C and IDL definitions of arrays. The Beginning Record Byte Number actually locates the first byte of the last General Housekeeping Record (GHR)[4] that occurred prior to the start of the current scan data (see introduction).

Type: long, INTEGER*4, Long.

2.3 Ending Record Byte Number

A number representing the byte offset from the beginning of the orbit file to the "end" of the last record for the current scan. The first byte of the file is considered to be byte zero. If the Ending Record Byte number is less than the Beginning Record Byte Number, then the scan data extend over two orbit files. The byte offset would then be from the beginning of the next orbit file. The Ending Record Byte Number actually locates the last byte of the first GHR that occurred after the end of the current scan data.

Type: long, INTEGER*4, Long.

2.4 Calendar Year

The calendar year.

Type:	short, INTEGER*2, Integer.
Example:	1993 is the year 1993; 2025 is the year 2025.

2.5 Day of Year

A number from 1 to 366 which represents the number of days, including the current day, since the beginning of the year. Note that a month and day can produce a different Day of Year if Calendar Year is a leap year.

Type: short, INTEGER*2, Integer.
Example: 20 is January 20; 366 is December 31 if Calendar Year is a leap year.

2.6 GMT Milliseconds

A number from 0 to 86,399,999 which represents the number of milliseconds that have elapsed since midnight Greenwich Mean Time (local mean solar time on the Greenwich meridian).

Type: long, INTEGER*4, Long.
Example: 1,000 is one second after midnight.

2.7 Scan Mode Number

A number equal to 7 or a number from 0 to 4 which indicates the RAIDS mode of operation for the present scan. The modes are summarized in Table 1. See the *RAIDS Experiment Users Manual*[5] for further information about modes of operation.

Type: unsigned char, BYTE, Byte.
Example: 0 indicates that all instruments are powered off and that RAIDS is waiting for the next command.

Table 1 - RAIDS Modes of Operation

Mode Number	Characteristic	Scan Platform	Spectrometers
0	Power-down standby	n/a	n/a
1	Monochromatic limb scans	Continuous scans	Fixed wavelength
2	Wavelength scans at selected altitudes	Preset altitudes	Scanning
3	Fixed altitude wavelength scans	Fixed altitude	Scanning
4	Stare	Fixed altitude	Fixed wavelength
7	Power-up standby	n/a	n/a

2.8 Instrument Status

A sequence of 8 toggle bits that form a number from 0 to 255 and indicates which of the eight RAIDS instruments are turned on and possibly taking data. A 0 in the bit's location indicates that the instrument is off. Table 2 shows which RAIDS instrument corresponds to which bit.

Type: unsigned char, BYTE, Byte.
Example: 255 means that all instruments are turned on; 128 means that only the EUV instrument is turned on.

Table 2 - Instrument Status Bit Values

Instrument Name	Bit Value
Extreme Ultraviolet Spectrograph	128
Far Ultraviolet Spectrograph	64
Middle Ultraviolet Spectrometer	32
Near Ultraviolet Spectrometer	16
Near Infrared Spectrometer	8
5890 Å Photometer	4
6300 Å Photometer	2
7774 Å Photometer	1

2.9 Status Verified

A sequence of 8 toggle bits that form a number from 0 to 255 which indicates that the status as reported in Instrument Status has been verified by a scientist or engineer. A 0 in the bit's location indicates that the status of that instrument has not been verified. Bits correspond to instruments as described in the table above.

Type: unsigned char, BYTE, Byte.
Example: 88 means that the FUV, NUV, and NIR instrument statuses have been verified.

2.10 Image ID

This number is generated by the RDBMS and points to an image table.

Type: long, INTEGER*4, Long.

2.11 Ionosonde/Radar Flag

A flag that indicates if any Ionosonde or Radar sites are "correlated" with the present scan. To be correlated, the site must be sufficiently near to the track of the subtangent point during the scan.

Type: char, LOGICAL, Byte.

2.12 UV Stars Flag

A flag that indicates if any stars in the RAIDS catalog are "correlated" with the present scan. The stars in the catalog comprise all stars known to emit strongly within the ultraviolet wavelength range covered by RAIDS. To be correlated with the scan, the star's right ascension (RA) and declination (DEC) must be sufficiently near to the RA and DEC ranges of the instrument's look direction during the scan.

Type: char, LOGICAL, Byte.

3. EPHEMERIS AND MODE DATA TABLE

3.1 GEI J2000 X

The X coordinate in centimeters of the satellite's position in the GEI J2000 system.

Type: long, INTEGER*4, Long.
Figure: GEI J2000 Coordinate System, Appendix A.

3.2 GEI J2000 Y

The Y coordinate in centimeters of the satellite's position in the GEI J2000 system.

Type: long, INTEGER*4, Long.
Figure: GEI J2000 Coordinate System, Appendix A.

3.3 GEI J2000 Z

The Z coordinate in centimeters of the satellite's position in the GEI J2000 system.

Type: long, INTEGER*4, Long.
Figure: GEI J2000 Coordinate System, Appendix A.

3.4 Satellite Altitude

The distance in centimeters from the *subsatellite point*, on the earth's surface, to the satellite.

Type: long, INTEGER*4, Long.
Figure: 2
Equation: Appendix C.1

3.5 Satellite Distance from Earth's Center

The magnitude in centimeters of the *satellite vector*.

Type: long, INTEGER*4, Long.

3.6 Satellite Geodetic Latitude

A number from -9000 to 9000, in hundredths of a degree, which represents the angle measured between the equatorial plane and the downward-projected normal to the surface of the *reference ellipsoid* at the *subsatellite point*. The angle is measured from the equatorial plane with positive angles being northward.

Type:	short, INTEGER*2, Integer.
Example:	4525 is 45.25° North Latitude; -9000 is the South Pole.
Figure:	2
Equation:	Appendix C.1

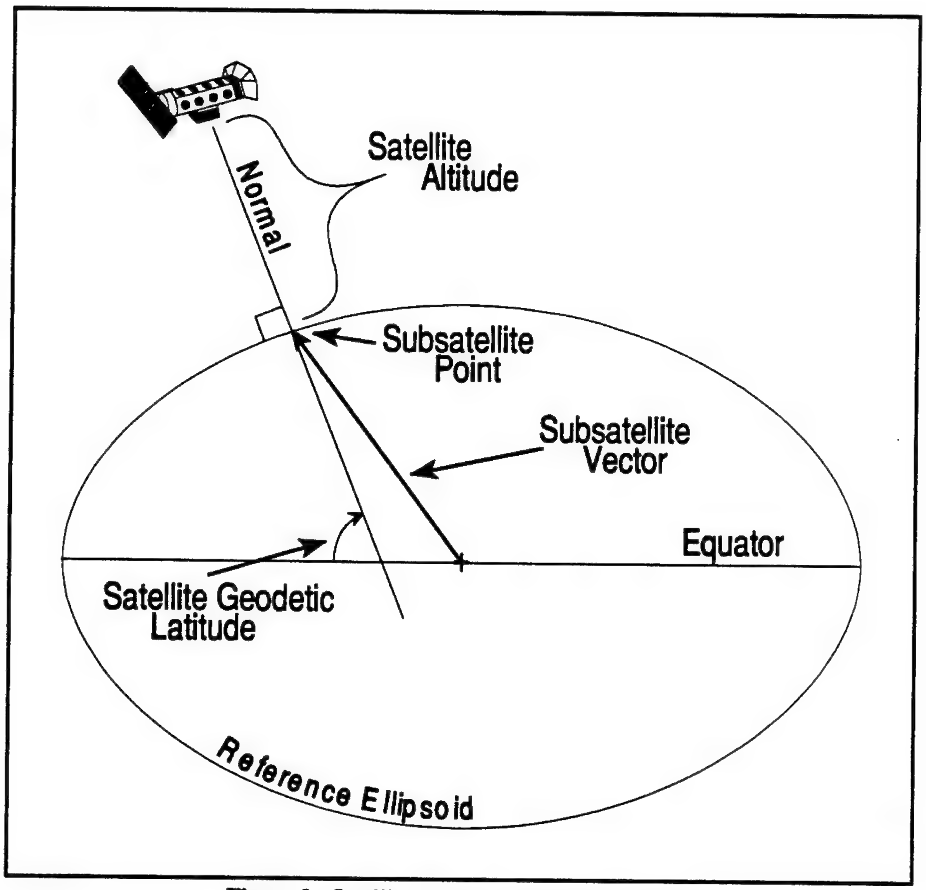

Figure 2 - Satellite altitude and geodetic latitude

3.7 Satellite Longitude

A number from -17999 to 18000 in hundredths of a degree which represents the angle measured positive eastward from the Greenwich meridian to the projection of the *satellite vector* onto the equatorial plane.

Type:	short, INTEGER*2, Integer.
Example:	12135 is 121.35° East Longitude; -500 is 5.00° West Longitude.
Figure:	3
Equation:	Appendix C.2

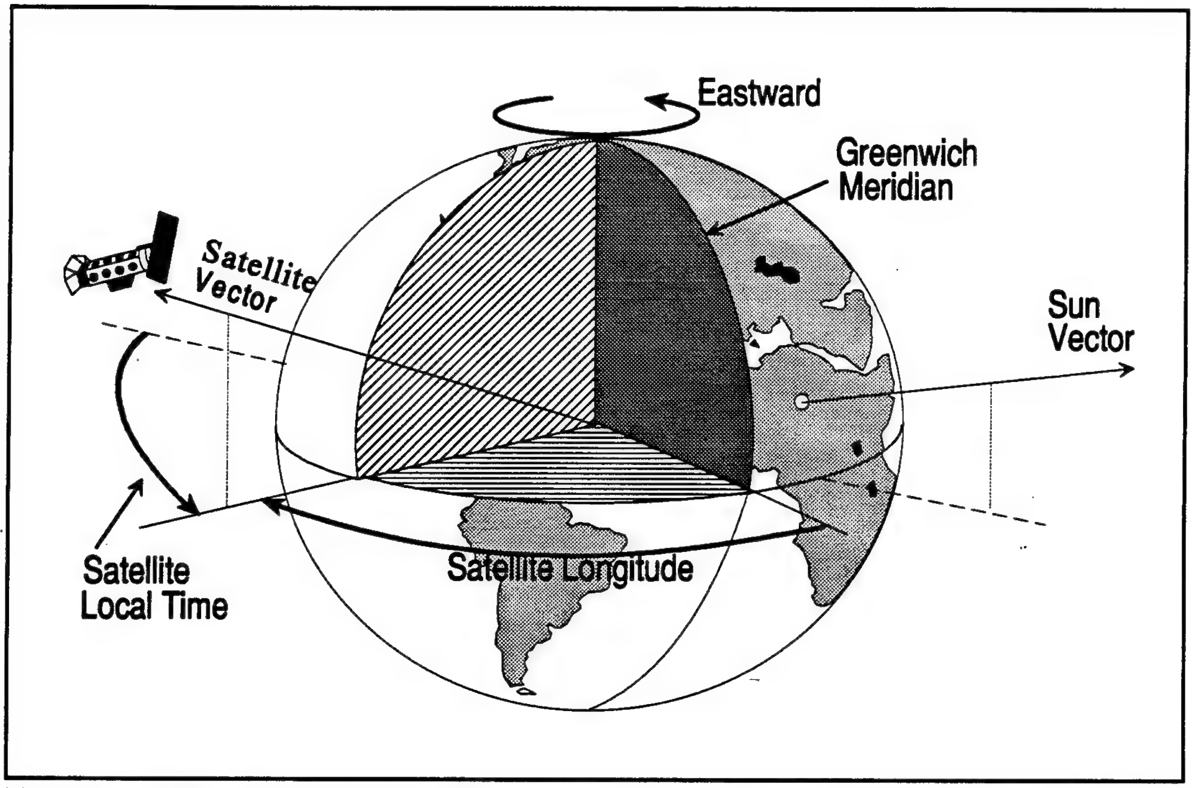

Figure 3 - Satellite longitude and local time. Note that satellite longitude is negative in this figure because it is being measured westward.

3.8 Satellite Local Time

A number from 0 to 35999 in hundredths of a degree which represents the satellite's longitude relative to "midnight". To find this angle the *satellite vector* and a vector with the opposite direction as the *sun vector* must both be projected onto the equatorial plane. The satellite local time is then measured eastward from the projection of the *sun vector* to the projection of the *satellite vector.*

Type:	long, INTEGER*4, Long.
Example:	18000 means that the satellite is at 1200 hours local time or noon.
Figure:	3
Equation:	Appendix C.3

3.9 Satellite Magnetic Latitude

A number from -9000 to 9000 in hundredths of a degree which represents the angle measured positive northward from the *magnetic equatorial plane* to the *satellite vector*. Note that this angle is independent of the shape of the earth.

Type:	short, INTEGER*2, Integer.
Example:	0 is the Magnetic Equatorial Plane; -9000 is the Magnetic South Pole.
Figure:	4
Equation:	Appendix C.4

3.10 Satellite Magnetic Longitude

A number from -17999 to 18000 in hundredths of a degree which represents the angle measured positive eastward from the $+X_{MAG}$ axis of the MAG system to the projection of the *satellite vector* onto the *magnetic equatorial plane.*

Type:	short, INTEGER*2, Integer.
Example:	-5378 is 53.78° West Magnetic Longitude.
Figure:	4
Equation:	Appendix C.5

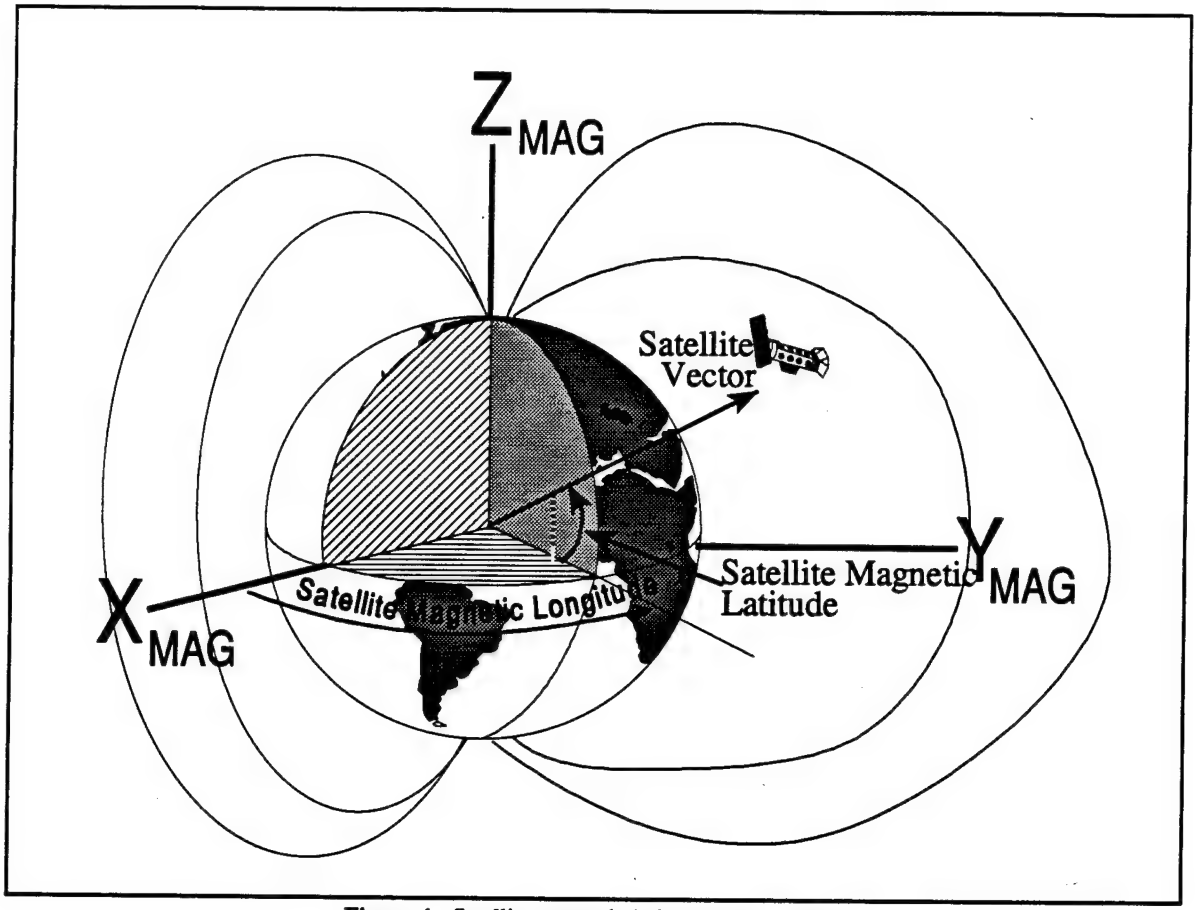

Figure 4 - Satellite magnetic latitude and longitude

3.11 Satellite Solar Azimuth Angle

A number from 0 to 35999 in hundredths of a degree which represents the angle measured eastward from "north" ($-X_H$ axis of SEZ system centered at the satellite) to the projection of the *satellite-sun vector* onto the plane of the horizon ($X_H Y_H$ plane).

Type:	long, INTEGER*4, Long.
Example:	18000 means that the sun is directly south of the satellite.
Figure:	5
Equation:	Appendix C.6

3.12 Satellite Solar Zenith Angle

A number from 0 to 18000 in hundredths of a degree which represents the angle from the local vertical (Z_H axis of the SEZ system centered at the satellite) to the *satellite-sun vector.*

Type:	short, INTEGER*2, Integer.
Example:	12031 means the sun is 120.31° from the local vertical, 30.31° below the local horizontal.
Figure:	5
Equation:	Appendix C.6

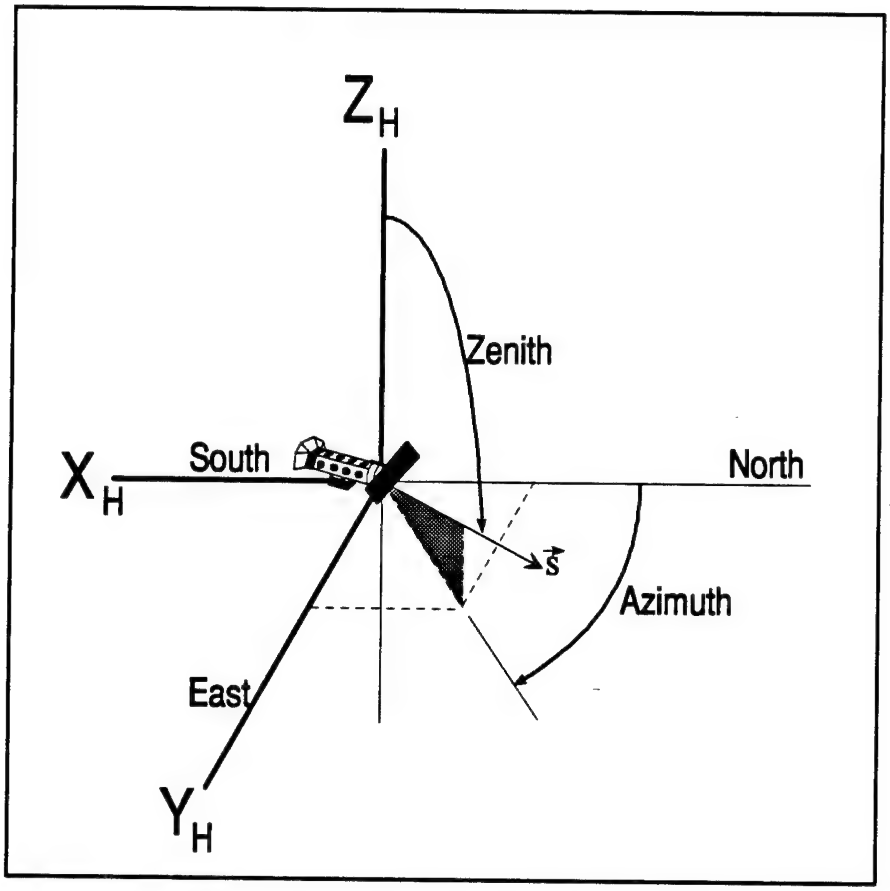

Figure 5 - Satellite solar azimuth and zenith angles or satellite lunar azimuth and zenith angles. Note that vector s is either the *satellite-sun vector* or the *satellite-moon vector*, and the $X_H Y_H$ plane is parallel to the plane that is tangent to the Earth's surface at the subsatellite point.

3.13 Satellite Lunar Azimuth Angle

The same as Satellite Solar Azimuth Angle, except that the projection of the *satellite-moon vector* onto the plane of the horizon is used.

Type: long, INTEGER*4, Long.
Figure: 5
Equation: Appendix C.7

3.14 Satellite Lunar Zenith Angle

The same as Satellite Solar Zenith Angle, except that the angle is measured between the local vertical and the *satellite-moon vector*.

Type: short, INTEGER*2, Integer.
Figure: 5
Equation: Appendix C.7

3.15 Satellite Pitch

A number between -17999 and 18000 in hundredths of a degree which represents the angle that the satellite has rotated about the $+Z_G$ axis of the SGR system. The right hand rule is used to define the positive sense of this angle. Satellite pitch, roll, and yaw are linearly interpolated between values given once a second in the Orbital Parameter Block of the *Circular File* Record[4]. This interpolation is based on the value of GMT Milliseconds which is defined above in the Scans Data Table. The "once a second" values of pitch, roll, and yaw used in the interpolation are known to a tenth of a degree in the case of a TIROS-N host.

Type: short, INTEGER*2, Integer.
Figure: 6

3.16 Satellite Roll

The same as Satellite Pitch, except that this angle represents the rotation about the $+Y_G$ axis.

Type: short, INTEGER*2, Integer.
Figure: 6

3.17 Satellite Yaw

The same as Satellite Pitch, except that this angle represents the rotation about the $+X_G$ axis.

Type: short, INTEGER*2, Integer.
Figure: 6

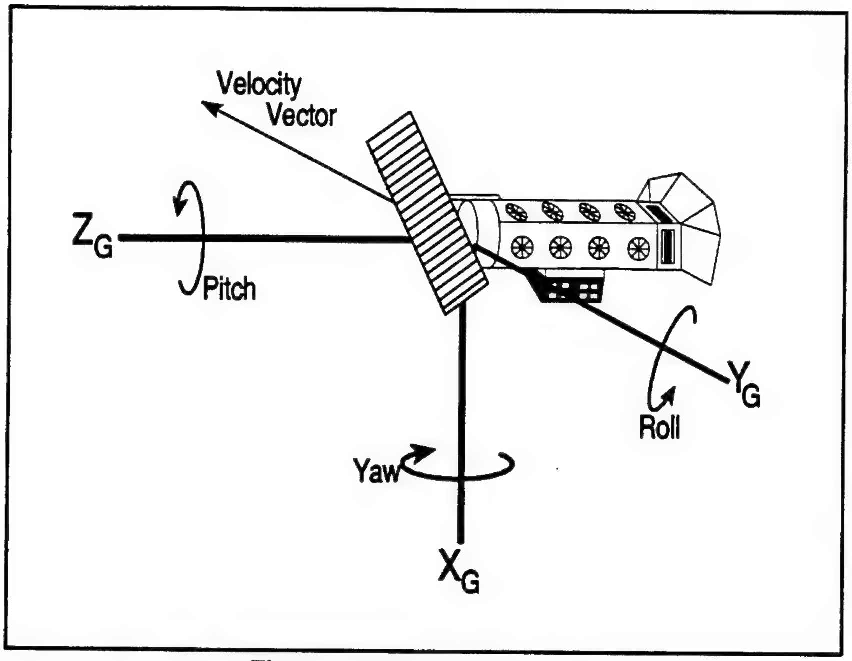

Figure 6 - Satellite pitch, roll, yaw

3.18 Satellite Velocity X

The rate of change in centimeters per second of the satellite's GEI J2000 X-coordinate.

Type: long, INTEGER*4, Long

3.19 Satellite Velocity Y

The rate of change in centimeters per second of the satellite's GEI J2000 Y-coordinate.

Type: long, INTEGER*4, Long.

3.20 Satellite Velocity Z

The rate of change in centimeters per second of the satellite's GEI J2000 Z- coordinate.

Type: long, INTEGER*4, Long.

3.21 α Step Number

A number between -150 and 8000 which represents the value of the platform position counter.

Type: short, INTEGER*2, Integer.

3.22 α

A number nominally between 1000 and 2650 in hundredths of a degree which represents the angle that the *line of sight vector* makes with the Y_BZ_B plane of the SF system. The angle is positive when measured "earthward" from the satellite horizontal. This value is calculated based on the – Step Number and the platform calibration function determined before launch. Note that – is only one factor that determines Tangent Altitude.

Type: short, INTEGER*2, Integer.
Example: 1532 means that the line of sight is 15.32° off the Y_BZ_B plane in the $+X_B$ direction.

3.23 Tangent Altitude

The distance in centimeters from the *subtangent point* to the *tangent point*.

Type: long, INTEGER*4, Long.
Figure: 7
Equation: Appendix C.8

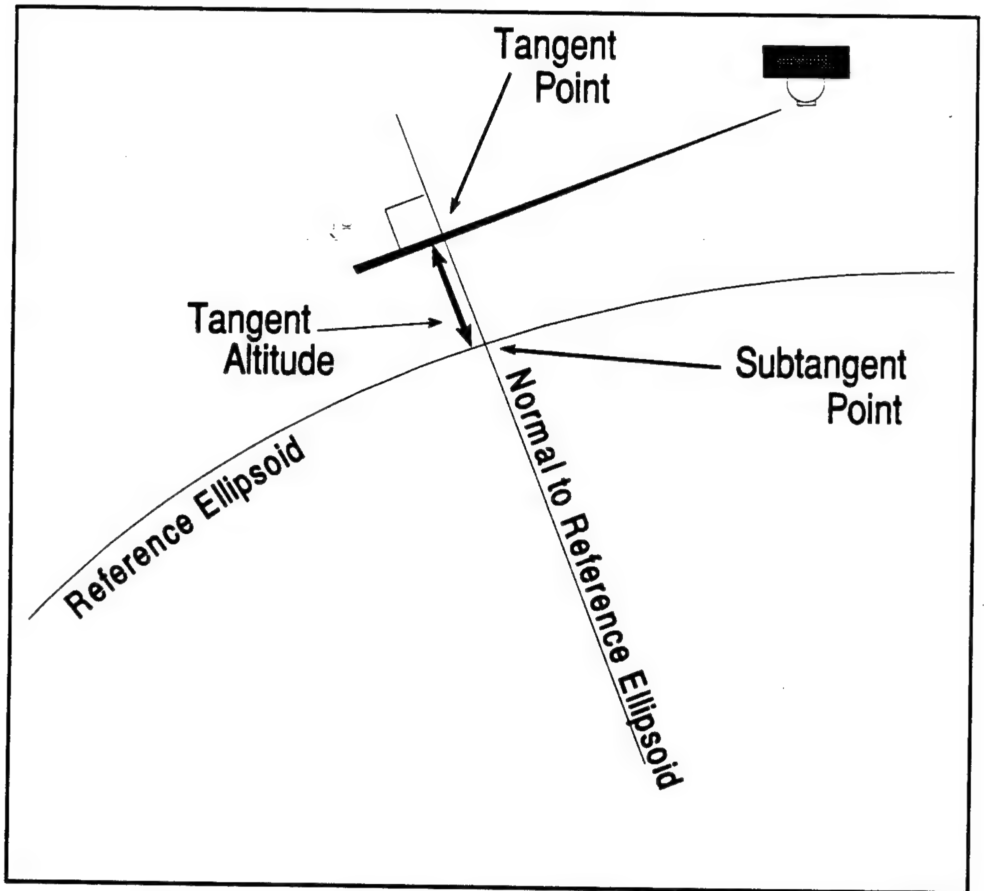

Figure 7 - Tangent altitude

3.24 Tangent Geodetic Latitude

The same as Satellite Geodetic Latitude, except that the angle is measured from the equatorial plane to the downward-projected normal of the *reference ellipsoid* at the *subtangent point.*

Type:	short, INTEGER*2, Integer.
Equation:	Appendix C.9.

3.25 Tangent Longitude

The same as Satellite Longitude, except that the projection of the *tangent vector* onto the equatorial plane is used.

Type:	short, INTEGER*2, Integer.
Equation:	Appendix C.10.

3.26 Tangent Local Time

The same as Satellite Local Time, except that the angle is measured to the projection of the *tangent vector* onto the equatorial plane.

Type: long, INTEGER*4, Long.
Equation: Appendix C.11.

3.27 Tangent Magnetic Latitude

The same as Satellite Magnetic Latitude, except that the angle is measured between the *magnetic equatorial plane* and the *tangent vector*.

Type: short, INTEGER*2, Integer.
Equation: Appendix C.12.

3.28 Tangent Magnetic Longitude

The same as Satellite Magnetic Longitude, except that the projection of the *tangent vector* onto the *magnetic equatorial plane* is used.

Type: short, INTEGER*2, Integer.
Equation: Appendix C.13

3.29 Tangent Solar Azimuth Angle

The same as Satellite Solar Azimuth Angle, except that the SEZ system is centered at the *tangent point* and the projection of *tangent-sun vector* onto the plane of the horizon is used.

Type: long, INTEGER*4, Long.

3.30 Tangent Solar Zenith Angle

The same as Satellite Solar Zenith Angle, except that the SEZ system is centered at the *tangent point* and the angle is measured between the local vertical and the *tangent-sun vector*.

Type: short, INTEGER*2, Integer.

3.31 Tangent Lunar Azimuth Angle

The same as Tangent Solar Azimuth Angle, except that the projection of the *tangent-moon vector* onto the plane of the horizon is used.

Type: long, INTEGER*4, Long.

3.32 Tangent Lunar Zenith Angle

The same as Tangent Solar Zenith Angle, except that the angle is measured between the local vertical and the *tangent-moon vector.*

Type: short, INTEGER*2, Integer.

3.33 Line of Sight Azimuth Angle

The same as Satellite Solar Azimuth Angle, except that the projection of the *line of sight vector* onto the plane of the horizon is used. The SEZ system is centered at the satellite.

Type: long, INTEGER*4, Long.

3.34 Line of Sight Zenith Angle

The same as Satellite Solar Zenith Angle, except that the angle is measured between the local vertical and the *line of sight vector*. The SEZ system is centered at the satellite.

Type: short, INTEGER*2, Integer.

3.35 Solar Right Ascension

A number from 0 to 235959 in hours, minutes, and seconds (hhmmss) which represents the angle measured positive eastward (+Y direction) from the +X axis of the GEI J2000 system to the projection of the *sun vector* onto the equatorial plane.

Type:	long, INTEGER*4, Long.
Example:	123447 is 12 hours, 34 minutes, and 47 seconds.
Figure:	8
Equation:	Appendix C.14.

3.36 Solar Declination

A number from -900000 to 900000 in degrees, minutes, and seconds (°° ' ' " ") which represents the angle measured positive northward (+Z direction of the GEI J2000 system) from the equatorial plane to the *sun vector*.

Type:	long, INTEGER*4, Long.
Example:	-872358 is -87 degrees, 23 minutes, and 58 seconds.
Figure:	8
Equation:	Appendix C.14.

3.37 Lunar Right Ascension

The same as Solar Right Ascension, except that the projection of the *moon vector* onto the equatorial plane is used.

Type: long, INTEGER*4, Long.
Equation: Appendix C.15.

3.38 Lunar Declination

The same as Solar Declination, except that the angle is measured between the equatorial plane and the *moon vector*.

Type: long, INTEGER*4, Long.
Equation: Appendix C.15

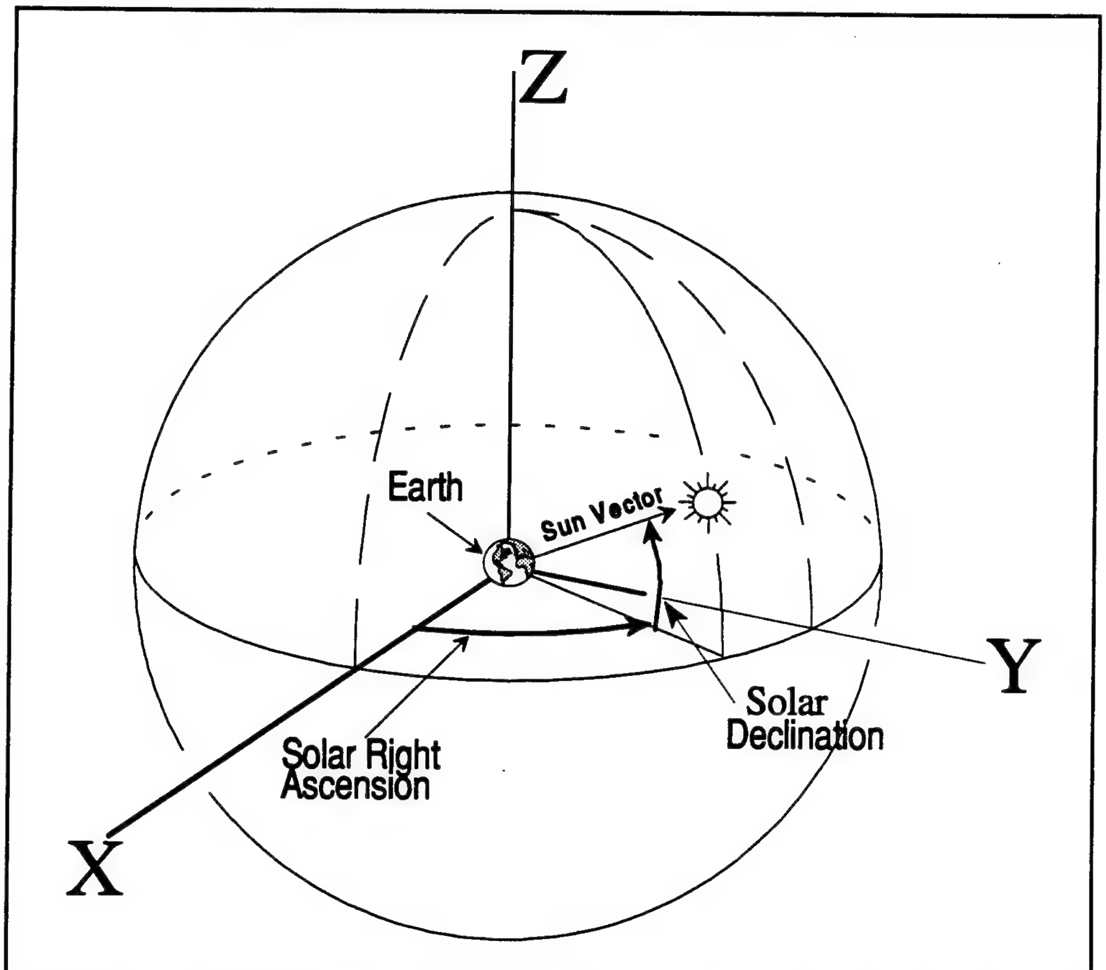

Figure 8 - Solar right ascension and declination

3.39 Satellite Right Ascension

The same as Solar Right Ascension, except that the projection of the *satellite vector* onto the equatorial plane is used.

Type: long, INTEGER*4, Long.

3.40 Satellite Declination

The same as Solar Declination, except that the angle is measured between the equatorial plane and the *satellite vector*.

Type: long, INTEGER*4, Long.

3.41 Line of Sight Right Ascension

The same as Solar Right Ascension, except that a vector starting at the GEI J2000 origin with the same direction as the *line of sight vector* is projected onto the equatorial plane.

Type: long, INTEGER*4, Long.

3.42 Line of Sight Declination

The same as Solar Declination, except that the angle is measured between the equatorial plane and a vector that has the same direction as the *line of sight vector* and that starts at the GEI J2000 origin.

Type: long, INTEGER*4, Long.

3.43 Line of Sight to Sun Angle

A number between 0 and 18000 in hundredths of a degree which represents the angle measured between the *line of sight vector* and the *satellite-sun vector*.

Type: short, INTEGER*2, Integer.
Figure: 9

3.44 Line of Sight to Moon Angle

The same as Line of Sight to Sun Angle, except that the angle is measured between the *line of sight vector* and the *satellite-moon vector*.

Type: short, INTEGER*2, Integer.

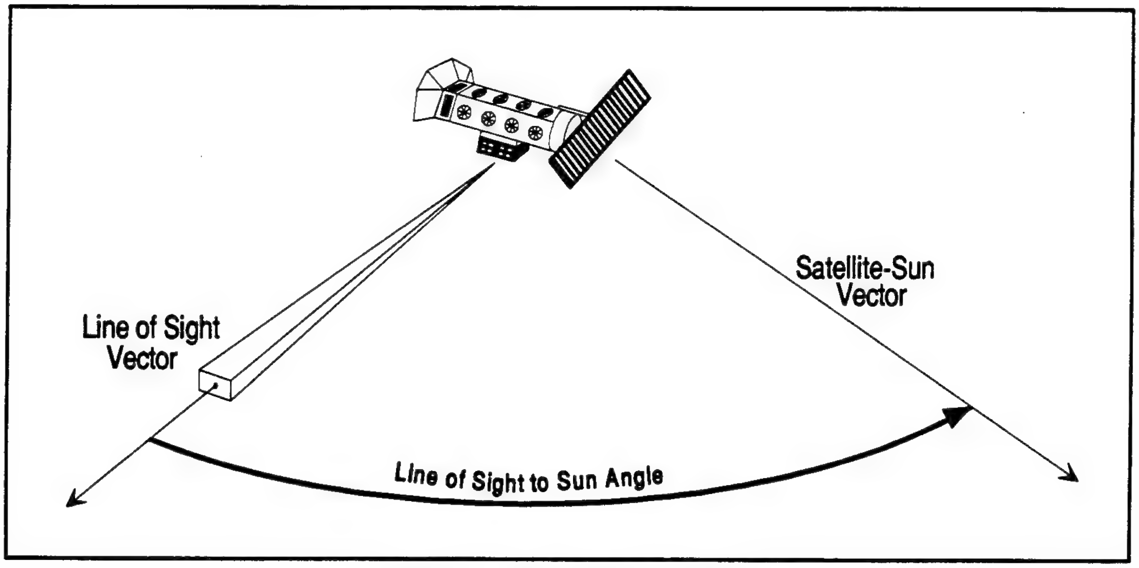

Figure 9 - Line of sight to sun angle

3.45 MUV λ Step Number

A number between -1 and 2000 which indicates the grating position step count of the MUV spectrometer. A value of -1 means that the spectrometer grating is scanning.

Type: short, INTEGER*2, Integer.

3.46 NUV λ Step Number

The same as MUV λ Step Number, except that this is for the NUV spectrometer.

Type: short, INTEGER*2, Integer.

3.47 NIR λ Step Number

The same as MUV λ Step Number, except that this is for the NIR spectrometer.

Type: short, INTEGER*2, Integer.

3.48 MUV λ

A number in angstroms which indicates the MUV spectrometer wavelength setting. This value is calculated based on the MUV λ Step Number and the current wavelength calibration function. A value of -1 means that the spectrometer grating is scanning.

Type:	short, INTEGER*2, Integer.
Example:	2450 means that the spectrometer is looking at 2450 angstroms.

3.49 NUV λ

The same as MUV λ, except that this is for the NUV spectrometer.

Type: short, INTEGER*2, Integer.

3.50 NIR λ

The same as MUV λ, except that this is for the NIR spectrometer.

Type: short, INTEGER*2, Integer.

3.51 EUV Grating Position

A toggle that indicates the position of the Extreme Ultraviolet Spectrograph's grating. Zero indicates that the grating is positioned for the shorter wavelength setting; any other value indicates the longer wavelength setting.

Type: unsigned char, BYTE, Byte.

3.52 Day/Night

A toggle that indicates the status of the RAIDS day/night clock. Zero indicates day; any other value indicates night. If RAIDS has been issued a sequence command, then the day/night toggle provides information as to which part of the sequence RAIDS is currently executing. See the *RAIDS Experiment Users Manual*[5] for further information about sequencer operation.

Type: unsigned char, BYTE, Byte.

ACKNOWLEDGMENT

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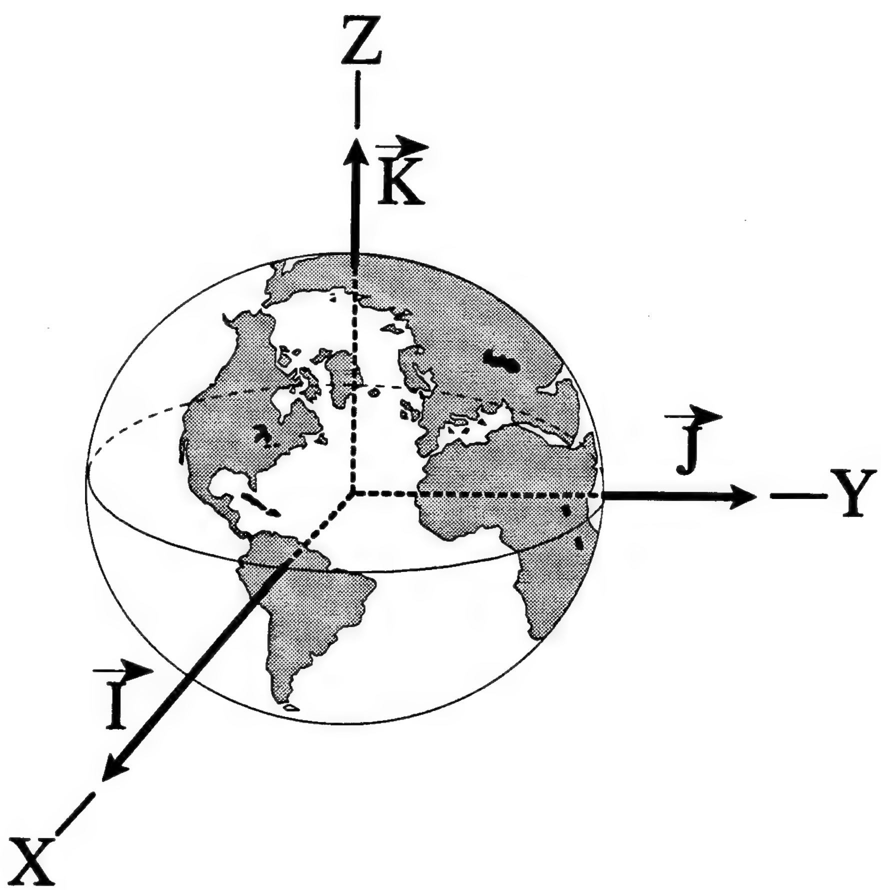
Appendix A

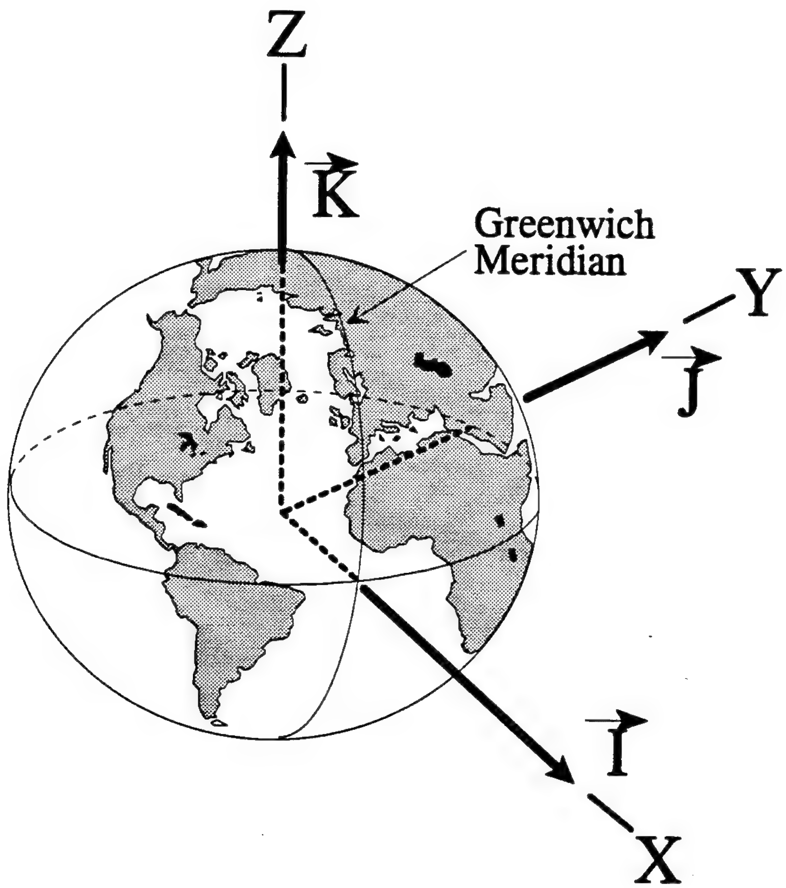
COORDINATE SYSTEMS[3,6-10]

A.1 Geocentric-Equatorial Inertial Coordinate System of the Year 2000



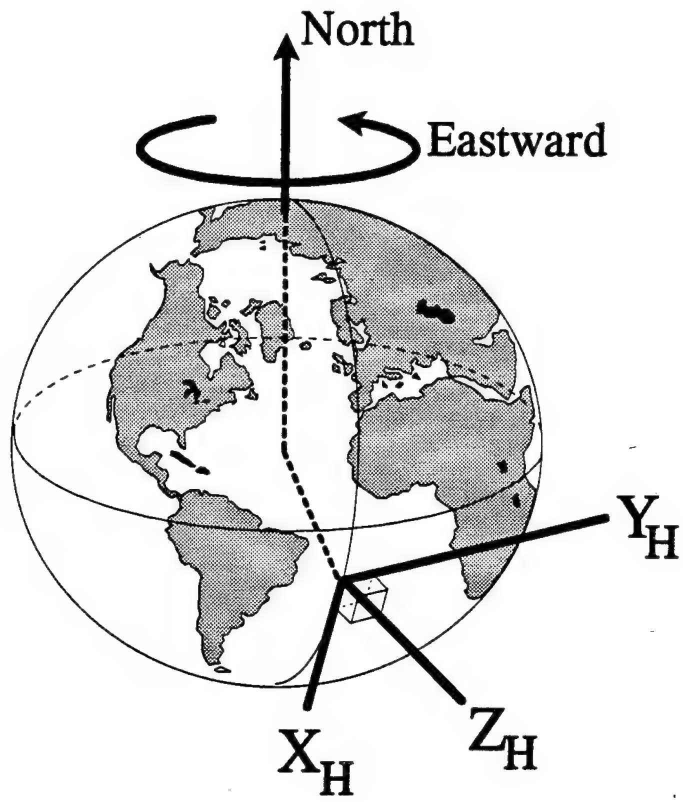
The Geocentric-Equatorial Inertial Coordinate System of the Year 2000 (GEI J2000) is an inertial system whose origin is located at the center of the earth. The fundamental plane is that of the earth's geographic equator. The positive X axis points in the direction of the ascending node of the ecliptic (mean plane of the earth's orbit around the Sun) on the earth's geographic equator at noon barycentric dynamical time on January 1, 2000 (Julian day number 2,451,545.0). The positive Z axis points in the direction of the earth's north pole, and the Y axis completes the right-handed orthogonal set.

A.2 Geographic Coordinate System



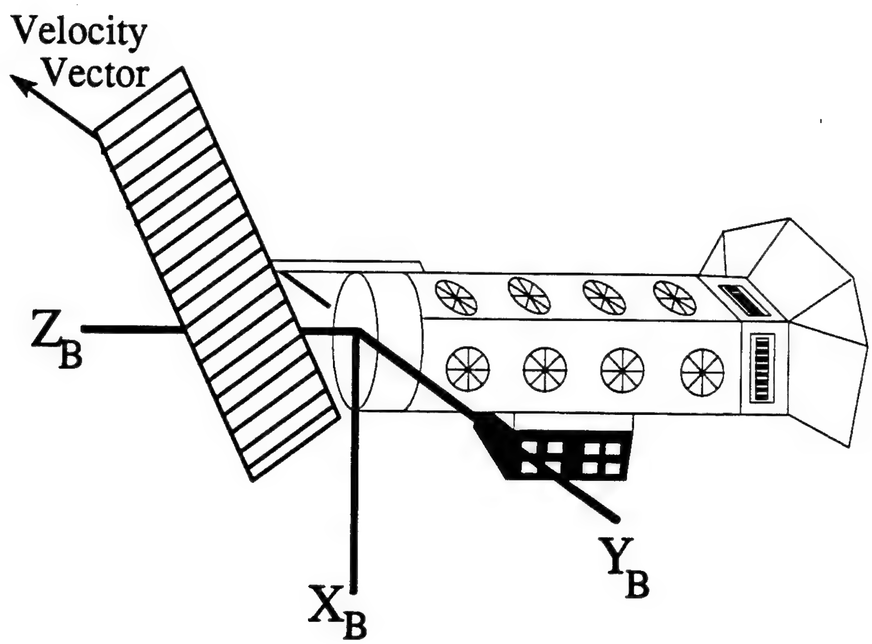
The geographic coordinate system (GEO) is a rotating system whose origin is located at the center of the earth. The fundamental plane is that of the earth's geographic equator. The positive X axis is fixed with the rotation of the earth so that it passes through the Greenwich meridian. The positive Z axis points in the direction of the earth's north pole, and the Y axis completes the right-handed orthogonal set.

A.3 Horizon Coordinate System



The Horizon Coordinate System (SEZ) is commonly referred to as a topocentric-horizon system. This means that the origin of the system is located at the observer, i.e. RAIDS. The local vertical, located on the near side of the *reference ellipsoid* and passing through the observer, defines the Z_H axis; the positive sense is away from the earth. The positive X_H axis points due south, while the positive Y_H axis points due east. The directions for east and south are interpreted as if the origin were on the earth's surface. The SEZ system is not an inertial reference frame.

A.4 Satellite-Fixed Coordinate System

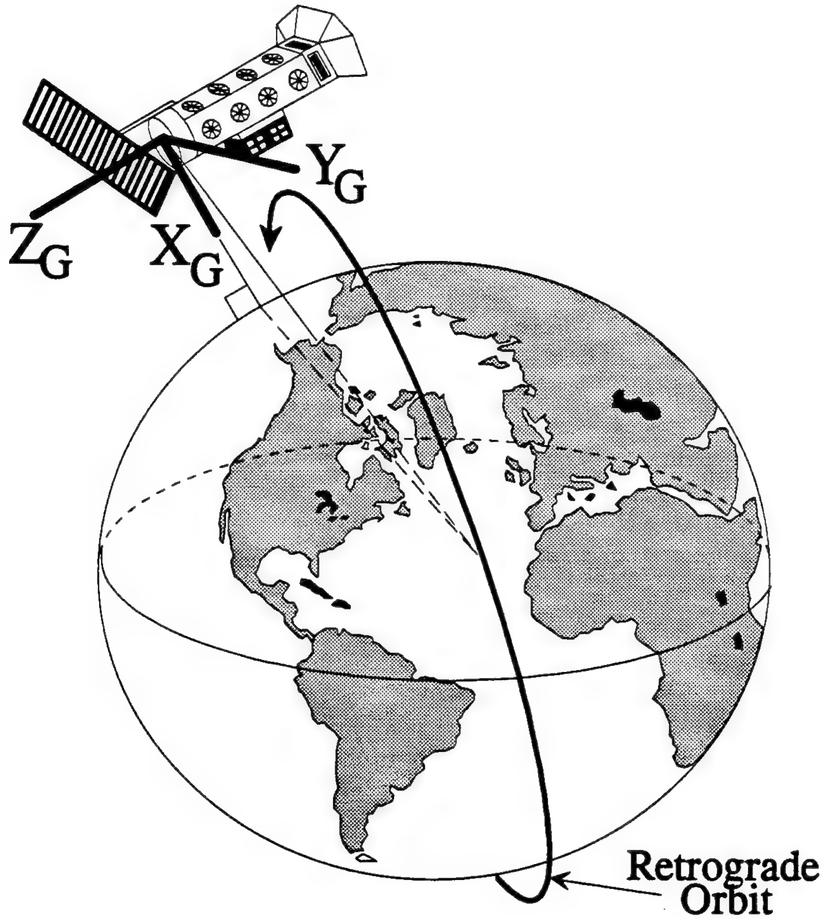


The Satellite-Fixed Coordinate System (SF) is a right-handed, body fixed-coordinate system. The SF coordinate system is defined on page 8-1 in reference 3 as follows:

> The Z_B (pitch) axis is normal to the separation plane and passes through the center of the separation ring; the positive sense of the Z_B axis is nominally along the positive orbit normal. The X_B (yaw) axis is normal to the earth-facing side of the spacecraft with the positive sense being directed towards the earth. The Y_B (roll) axis completes the right-handed orthogonal triad; the positive sense of the roll axis is nominally opposite to the instantaneous velocity vector of the satellite. The origin of the reference coordinate system is located on the plane of separation between the spacecraft and its booster.

Note that the phrase "reference coordinate system" refers to the SF system. Given that RAIDS will probably fly on a satellite other than a NOAA TIROS-N, some of the terminology of this description might change. However, the definition shown by the above figure will likely remain the same.

A.5 Satellite Geodetic-Reference Coordinate System

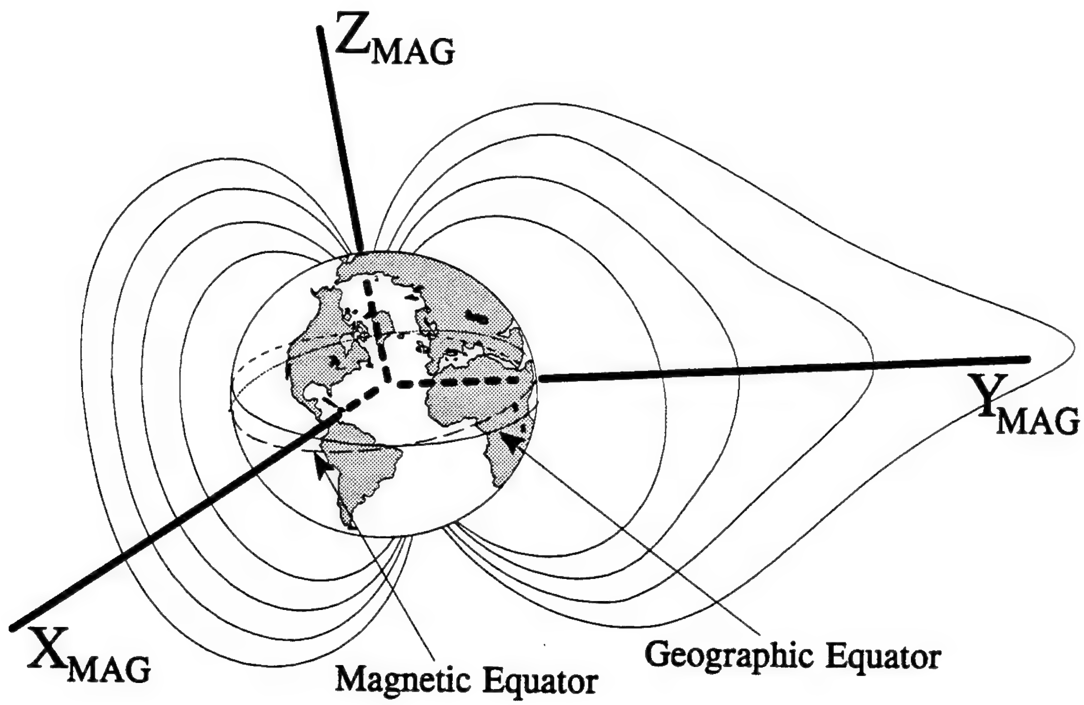


The Satellite Geodetic-Reference Coordinate System (SGR) is also defined in reference 3 as follows:

> The local geodetic reference represents the nominal required directions for the spacecraft coordinate reference. The X_G axis is a line through the origin of the spacecraft coordinate reference and normal to the reference geoid on the near side. X_G is positive from the spacecraft toward the earth. The Z_G axis is a line normal to the X_G axis and to the instantaneous inertial velocity vector. The positive Z_G axis lies on the sunlit side of the plane formed by the velocity vector and the X_G axis. The Y_G axis completes the right-handed orthogonal set.

Note that "local geodetic reference" refers to the SGR system and that "spacecraft coordinate reference" refers to the SF system.

A.6 Geomagnetic Coordinate System



The Geomagnetic Coordinate System (MAG) is a non-inertial system that rotates with the earth. This paper assumes a Centered Dipole Geomagnetic coordinate system. Its origin is located at the geographic center of the earth with the Z_{MAG} axis running along the earth's magnetic dipole. The positive sense of the Z_{MAG} axis is towards the north pole from the center of the earth. The positive Y_{MAG} axis is defined as the cross product, $Z_{GEI} \times Z_{MAG}$, of the geographic north pole (+Z GEI J2000 axis) and the Z_{MAG} axis. Finally, the positive X_{MAG} axis is defined as $Y_{MAG} \times Z_{MAG}$. Note that the $X_{MAG}Y_{MAG}$ plane defines the magnetic equator.

Appendix B

GLOSSARY

Circular File	NOAA file containing the satellite data and RAIDS instrument data for ingest into RAIDS Data Processing Facility (DPF). The data will be transferred from the NOAA Circular File to the RAIDS DPF over Internet, one pass (orbit) at a time.
Line of Sight Vector	The vector pointing from RAIDS in the direction of the field of view of the instruments mounted on the scanning platform.
Magnetic Equatorial Plane	The plane containing the X_{MAG} and Y_{MAG} axes of the Geomagnetic Coordinate System (MAG). See appendix A for information about coordinate systems. Note that this plane passes through the center of the earth.
Moon Vector	The vector from the center of the earth to the center of the moon.
Reference Ellipsoid	A model that approximates the surface of the earth, commonly referred to as "mean sea level" or "geoid". Values used for this model come from *The Astronomical Almanac*, page K5[3].
Satellite Vector	The vector from the center of the earth to the satellite's position. This vector has components equal to the GEI J2000 X, Y, and Z coordinates.
Satellite-Moon Vector	The vector from the satellite's position (origin of Satellite-Fixed coordinate system, Appendix A.4) to the center of the moon.
Satellite-Sun Vector	The vector from the satellite's position (origin of Satellite-Fixed coordinate system, Appendix A.4) to the center of the sun.
Subsatellite Point	The point on the *reference ellipsoid* where the outward normal to the *reference ellipsoid* passes through the satellite's position.
Subsatellite Vector	The vector from the center of the earth to the *subsatellite point*. See Figure 2, page 8.
Subtangent Point	The point on the *reference ellipsoid* where the local vertical is perpendicular to the *line of sight vector* and for which the distance to the line of sight vector is a minimum.
Subtangent Vector	The vector from the center of the earth to the *subtangent point*.

Sun Vector The vector from the center of the earth to the center of the sun.

Tangent Point The point along the *line of sight vector* where the distance between the *line of sight vector* and the *reference ellipsoid* is a minimum. The local vertical at the *subtangent point* passes through the tangent point.

Tangent-Moon Vector The vector from the *tangent point* to the center of the moon.

Tangent-Sun Vector The vector from the *tangent point* to the center of the sun.

Tangent Vector The vector from the center of the earth to the *tangent point.*

Appendix C

EQUATIONS

The equations and algorithms below are central to computing various attributes described in Sections 2 and 3. Some aspects of the notation and the mathematical functions require further specification. The notation for unit vectors in any coordinate system is $\hat{x}$, $\hat{y}$, and $\hat{z}$. If a given attribute (e.g. Satellite altitude) is discussed in the context of a particular coordinate system, then the reader should assume that $\hat{x}$, $\hat{y}$, and $\hat{z}$ are the unit vectors in that coordinate system. The definitions of $\hat{x}$, $\hat{y}$, and $\hat{z}$ can change from attribute to attribute. In all cases, the equations below were written to directly correspond with the actual C code.

Several equations listed below implement the arc tangent ($\tan^{-1}$) function. The arc tangent ($\tan^{-1}$) is computed with the C function *atan2*. This function returns a value between $-\pi$ and π radians. It computes atan2(r_1/r_0) using the signs of r_1 and r_0 to determine the quadrant of the arc tangent. Atan2 is well defined when either r_1 or r_2 is zero, but may flag a domain error if both arguments are zero[14].

C.1 Satellite Altitude and Geodetic Latitude[8]

The following items are required for the calculation:

$$\vec{R}_{GEI} = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z} \tag{1}$$

$$r = |\vec{R}_{GEI}| = \sqrt{r_0^2 + r_1^2 + r_2^2} \tag{2}$$

where $\mathbf{R}_{GEI}$ is a three dimensional GEI vector in centimeters from the center of the Earth to the satellite. Define

$$r_c = a_e \sqrt{\frac{1-(2f-f^2)}{1-(2f-f^2)\cos^2\phi_s'}} \tag{3}$$

$$\delta = \tan^{-1}\left(\frac{r_2}{\sqrt{r_0^2+r_1^2}}\right), \quad -90° \le \delta \le 90° \tag{4}$$

where:

a_e = the equatorial radius of the Earth = 637814000.0 cm.

f = the flattening factor of the Earth = 1.0/298.257.
ϕ_s' = the geocentric latitude of the subsatellite point.

At this step, ϕ_s' is initially assumed to equal δ. The geodetic latitude (ϕ_s) and altitude (A), respectively are as follows:

$$\phi_s = \tan^{-1}\left(\frac{1}{(1-f)^2}\tan\phi_s'\right), \qquad -90° \le \phi_s \le 90° \tag{5}$$

$$A = \sqrt{r^2 - r_c^2\sin^2(\phi_s - \phi_s')} - r_c\cos(\phi_s - \phi_s') \ . \tag{6}$$

Given the above quantities, define updated quantities via equations (7) and (8):

$$\Delta\phi_s' = \sin^{-1}\left(\frac{A}{r}\sin(\phi_s - \phi_s')\right) \tag{7}$$

$$\phi_s' = \delta - \Delta\phi_s' \ . \tag{8}$$

Equations (3) - (8) are repeated until the new ϕ_s' is within 1×10^{-10} of the previous value. When this occurs ϕ_s is the calculated geodetic latitude in radians and A is the altitude in centimeters. The geodetic latitude is then converted to hundredths of a degree by multiplying by $18000/\pi$ and rounding to the nearest whole number. If this loop is performed 1000 times it will cause the function to stop and issue an error message.

C.2 Satellite Longitude

The following vector is required for the calculation:

$$\vec{R}_{GEO} = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z}$$

where $\mathbf{R_{GEO}}$ is a three dimensional GEO vector from the center of the Earth to the satellite.

Calculate the satellite longitude (*sat_long*) as follows:

$$sat\_long = \begin{cases} 0.0 & \text{for} \quad r_0 = r_1 = 0 \\ \tan^{-1}\left(\frac{r_1}{r_0}\right) \cdot \frac{180}{\pi} & \text{otherwise.} \end{cases}$$

Longitude is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.3 Satellite Local Time

The following items are required for the calculation:

ra_{sat} = right ascension of the satellite in degrees.
ra_{sun} = right ascension of the sun in degrees.

Calculate the satellite local time (τ_{local}) as follows:

$$\tau_{local} = (ra_{sat} - ra_{sun}) - 180.0$$

If the computed satellite local time (τ_{local}) is greater than or equal to 360.0, subtract 360.0 to arrive at the final result. If satellite local time is less than 0.0 , add 360.0. Local time is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.4 Satellite Magnetic Latitude

The following vector is required for the calculation:

$$\vec{R}_{MAG} = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z}$$

where $\mathbf{R}_{MAG}$ is a three-dimensional MAG vector from the center of the earth to the satellite.

Calculate the satellite magnetic latitude (sat_lat_{mag}) as follows:

$$sat\_lat_{mag} = \begin{cases} 0.0 & \text{for} \quad r_0 = r_1 = r_2 = 0 \\ \tan^{-1}\left(\dfrac{r_2}{\sqrt{r_0^2 + r_1^2}}\right) \cdot \dfrac{180}{\pi} & \text{otherwise} \end{cases}$$

Latitude is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.5 Satellite Magnetic Longitude

The following vector is required for the calculation:

$$\vec{R}_{MAG} = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z}$$

where $\mathbf{R}_{MAG}$ is a three-dimensional MAG vector from the center of the earth to the satellite.

Calculate the satellite magnetic longitude (sat_long_{mag}) as follows:

$$sat\text{-}long_{mag} = \begin{cases} 0.0 & \text{for} \quad r_0 = r_1 = 0 \\ \tan^{-1}\left(\dfrac{r_1}{r_0}\right) \cdot \dfrac{180}{\pi} & \text{otherwise.} \end{cases}$$

Longitude is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.6 Satellite Solar Azimuth and Zenith

The following vector is required for the calculation:

$$\vec{R}_{SEZ}(\odot) = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z}$$

where $\mathbf{R}_{SEZ}(\odot)$ is the SEZ satellite-sun vector.

Calculate the solar azimuth (*SA*) as follows:

$$SA = \begin{cases} 0.0 & \text{for} \quad r_0 = r_1 = 0 \\ \tan^{-1}\left(\dfrac{r_1}{-r_0}\right) \cdot \dfrac{180}{\pi} & \text{otherwise.} \end{cases}$$

If *SA* is less than 0.0, add 360.0 to obtain the final result.

Calculate the solar zenith (*SZ*) as follows:

$$SZ = \begin{cases} 90.0 & \text{for} \quad r_0 = r_1 = r_2 = 0 \\ \tan^{-1}\left(\dfrac{\sqrt{r_0^2 + r_1^2}}{r_2}\right) \cdot \dfrac{180}{\pi} & \text{otherwise.} \end{cases}$$

If *SZ* is less than 0.0, add 180.0.

Solar azimuth and zenith are converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.7 Satellite Lunar Azimuth and Zenith

The following vector is required for the calculation:

$$\vec{R}_{SEZ}(\text{☾}) = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z}$$

where $\mathbf{R}_{SEZ}(\text{☾})$ is the SEZ satellite-moon vector.

Calculate the satellite lunar azimuth (LA) as follows:

$$LA = \begin{cases} 0.0 & \textit{for} \quad r_0 = r_1 = 0 \\ \tan^{-1}\left(\dfrac{r_1}{-r_0}\right) \cdot \dfrac{180}{\pi} & \textit{otherwise.} \end{cases}$$

If LA is less than 0.0, add 360.0 to obtain the final result.

Calculate the satellite lunar zenith (LZ) as follows:

$$LZ = \begin{cases} 90.0 & \textit{for} \quad r_0 = r_1 = r_2 = 0 \\ \tan^{-1}\left(\dfrac{\sqrt{r_0^2 + r_1^2}}{r_2}\right) \cdot \dfrac{180}{\pi} & \textit{otherwise.} \end{cases}$$

If LZ is less than 0.0, add 180.0.

Lunar azimuth and zenith are converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.8 Tangent Altitude

The following vectors are required for the calculation:

$$\vec{R}_{GEI} = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z} \tag{1}$$

$$\vec{M}_{GEI} = m_0 \cdot \hat{x} + m_1 \cdot \hat{y} + m_2 \cdot \hat{z} \tag{2}$$

where:

$\mathbf{R}_{GEI}$ is a three dimensional GEI vector in centimeters from the center of the Earth to the satellite,
$\mathbf{M}_{GEI}$ is the line of sight vector in centimeters.

Define unit vectors:

$$\hat{r} \equiv \frac{\vec{R}}{|R|} \; ; \quad \hat{m} \equiv \frac{\vec{M}}{|M|} \tag{3}$$

Using the definition of scalar product, the supplement, θ, of the angle between the vectors $\mathbf{r}$ and $\mathbf{m}$ can be found:

$$-\cos\theta = \hat{m}\cdot\hat{r} \ . \qquad (4)$$

The tangent altitude unit vector, $\hat{a}$, can now be calculated:

$$\hat{a} = \frac{\hat{r}}{\sin\theta} + \frac{\hat{m}}{\tan\theta} \ . \qquad (5)$$

The next step is to calculate the subtangent point. The calculation yields two candidates: one for each "side" of the ellipsoid relative to the line of sight. There are three different cases to consider when calculating the subtangent point depending on which, if any, components of the tangent altitude unit vector $\hat{a} \equiv (a_0, a_1, a_2)$ are zero. The last component needs to be nonzero.

Case 1: If $a_2 = 0$ then skip to equation (6).

Case 2: If $a_2 = 0$ and $a_0 = 0$; rotate array around so last element is nonzero: $a^r_0 = a_1$; $a^r_1 = a_2$; $a^r_2 = a_0$. Perform equations (6) through (16) using a^r in place of a. After equation (16) return here.

The calculated subtangent point is in rotated variables, let: $s^r_0 = s_0$; $s^r_1 = s_1$; $s^r_2 = s_2$. Rotate the array back around into the proper order: $s_0 = s^r_2$; $s_1 = s^r_0$; $s_2 = s^r_1$. Return to equation (17)

Case 3: If $a_2 = 0$ and $a_1 = 0$:
Rotate the altitude vector array so the last element is non zero;
$a^r_0 = a_2$; $a^r_1 = a_0$; $a^r_2 = a_1$. Perform equations (6) through (16) replacing a with a_r. After equation (16) return here.

The calculated subtangent point is in rotated variables, let: $s^r_0 = s_0$; $s^r_1 = s_1$; $s^r_2 = s_2$. Rotate the array back around into the proper order: $s_0 = s^r_1$; $s_1 = s^r_2$; $s_2 = s^r_0$. Return to equation (17).

Calculate the altitude component ratios, η_{01} and η_{12}:

$$\eta_{02} = \frac{\hat{a}_0}{\hat{a}_2} \ ; \quad \eta_{12} = \frac{\hat{a}_1}{\hat{a}_2} \qquad (6)$$

Calculate the first subtangent point $p^{(1)}$ and the distance d_1 to the satellite: first define the vector b, for which $b_0 = b_1$ = earth equatorial radius = 637814000.0 cm, and b_2 = earth polar radius = $b_0(1.0 - f)$, where f is the flattening factor = 1.0/298.257. Then we have

$$p_2^{(1)} = \frac{b_2}{\sqrt{\frac{b_0^2}{b_2^2}\eta_{02}^2 + \frac{b_1^2}{b_2^2}\eta_{12}^2 + 1}} \qquad (7)$$

$$p_0^{(1)} = p_2^{(1)} \frac{b_0^2}{b_2^2} \eta_{02} \tag{8}$$

$$p_1^{(1)} = p_2^{(1)} \frac{b_1^2}{b_2^2} \eta_{12} \tag{9}$$

$$d_1 = (r_0 - p_0^{(1)})^2 + (r_1 - p_1^{(1)})^2 + (r_2 - p_2^{(1)})^2 \tag{10}$$

Calculate the second subtangent point $\mathbf{p}^2$ and the distance to the satellite d_2:

$$p_0^{(2)} = -p_0^{(1)} \tag{11}$$

$$p_1^{(2)} = -p_1^{(1)} \tag{12}$$

$$p_2^{(2)} = -p_2^{(1)} \tag{13}$$

$$d_2 = (r_0 - p_0^{(2)})^2 + (r_1 - p_1^{(2)})^2 + (r_2 - p_2^{(2)})^2 \tag{14}$$

The shorter of the two distances is the subtangent point we want:

$$if \;\; d_1 < d_2; \qquad s_0 = p_0^{(1)}; \quad s_1 = p_1^{(1)}; \quad s_2 = \tag{15}$$

$$if \;\; d_1 > d_2; \qquad s_0 = p_0^{(2)}; \quad s_1 = p_1^{(2)}; \quad s_2 = \tag{16}$$

The subtangent point vector, S, is now known:

$$\vec{S} = s_0 \cdot \hat{x} + s_1 \cdot \hat{y} + s_2 \cdot \hat{z} \;\; . \tag{17}$$

Using the scalar product and some manipulation, the magnitude of the tangent altitude vector, a, can be found.

$$S_r = \vec{S} \cdot \hat{r}; \qquad S_m = \vec{S} \cdot \hat{m} \tag{18}$$

$$R' = \frac{S_r + S_m \cdot \cos(\theta)}{\sin^2(\theta)} \tag{19}$$

$$a = (R - R') \cdot \sin(\theta) \tag{20}$$

C.9 Tangent Geodetic Latitude

The following GEI vector is required for the calculation:

$$\hat{a} = a_0 \cdot \hat{x} + a_1 \cdot \hat{y} + a_2 \cdot \hat{z}$$

where $\hat{a}$ is the tangent altitude unit vector that was found in the Tangent Altitude Section, C.8.

Calculate the tangent geodetic latitude (*tan_lat*) as follows:

$$tan\_lat = \begin{cases} 0.0 & for \quad a_0 = a_1 = a_2 = 0 \\ \tan^{-1}\left(\dfrac{a_2}{\sqrt{a_0^2 + a_1^2}}\right) \cdot \dfrac{180}{\pi} & otherwise \end{cases}$$

Tangent geodetic latitude is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.10 Tangent Longitude

The following vector is required for the calculation:

$$\vec{T}_{GEO} = t_0 \cdot \hat{x} + t_1 \cdot \hat{y} + t_2 \cdot \hat{z}$$

where T_{GEO} is the GEO tangent point position vector in centimeters. This vector is found by first adding the subtangent point vector, s, and the tangent altitude vector, a, found in the **Tangent Altitude** Section, C.8. The resulting vector is the tangent point in the GEI system. That must then be transformed into the GEO system by the method in Appendix D.

Calculate the tangent longitude (*tan_long*) as follows:

$$tan\text{–}long = \begin{cases} 0.0 & for \quad t_0 = t_1 = 0 \\ \tan^{-1}\left(\dfrac{t_1}{t_0}\right) \cdot \dfrac{180}{\pi} & otherwise \end{cases}$$

Longitude is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.11 Tangent Local Time

The following items are required for the calculation:

ra_{tan} = right ascension of the tangent point in degrees.
ra_{sun} = right ascension of the sun in degrees.

Calculate the tangent local time (τ_{tan}) as follows:

$$\tau_{tan} = (ra_{tan} - ra_{sun}) - 180.0$$

If the computed tangent local time (τ_{tan}) is greater than or equal to 360.0, subtract 360.0 to obtain the final result. If tangent local time is less than 0.0 add 360.0. Tangent local time is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.12 Tangent Magnetic Latitude

The following vector is required for the calculation:

$$\vec{T}_{MAG} = t_0 \cdot \hat{x} + t_1 \cdot \hat{y} + t_2 \cdot \hat{z}$$

where $\mathbf{T}_{MAG}$ is the MAG tangent point position vector in centimeters. This vector is found by adding the subtangent point vector and the tangent altitude vector found in the **Tangent Altitude** Section, C.8. The resulting vector is the tangent point in the GEI system. That must then be transformed into the MAG system.

Calculate the tangent magnetic latitude (*tan_lat$_{MAG}$*) as follows:

$$tan\text{–}lat_{MAG} = \begin{cases} 0.0 & for \quad t_0 = t_1 = t_2 = 0 \\ \tan^{-1}\left(\dfrac{t_2}{\sqrt{t_0^2 + t_1^2}}\right) \cdot \dfrac{180}{\pi} & otherwise \end{cases}$$

Latitude is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.13 Tangent Magnetic Longitude

The following vector is required for the calculation:

$$\vec{T}_{MAG} = t_0 \cdot \hat{x} + t_1 \cdot \hat{y} + t_2 \cdot \hat{z}$$

where $\mathbf{T}_{MAG}$ is the MAG tangent point position vector in centimeters. This vector is found by first adding the subtangent point vector and the tangent altitude vector found in the **Tangent Altitude** Section, C.8. The resulting vector is the tangent point in the GEI system. That must then be transformed into the MAG system by the method in Appendix D.

Calculate the tangent magnetic longitude (tan_long_{MAG}) as follows:

$$\text{tan–}long_{MAG} = \begin{cases} 0.0 & \textit{for} \quad t_0 = t_1 = 0 \\ \tan^{-1}\left(\dfrac{t_1}{t_0}\right) \cdot \dfrac{180}{\pi} & \textit{otherwise} \end{cases}$$

Longitude is converted to hundredths of a degree by multiplying by 100 and rounding to the nearest whole number.

C.14 Solar Right Ascension and Declination

The following vector is required for the calculation:

$$\vec{R}_{GEI}(\odot) = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z}$$

where $\mathbf{R}_{GEI}(\odot)$ is a three dimensional GEI vector in centimeters from the center of the earth to the center of the sun. This vector is calculated using the Jet Propulsion Laboratory (JPL) Export Ephemeris Package.

Calculate the right ascension (ra) as follows:

$$ra = \begin{cases} 0.0 & \textit{for} \quad r_0 = r_1 = 0 \\ \tan^{-1}\left(\dfrac{r_1}{r_0}\right) \cdot \dfrac{180}{\pi} & \textit{otherwise} \end{cases}$$

If ra is less than 0.0, add 360.0.

Calculate the declination (*dec*) as follows:

$$dec = \begin{cases} 0.0 & \text{for} \quad r_0 = r_1 = r_2 = 0 \\ \tan^{-1}\left(\dfrac{r_2}{\sqrt{r_0^2 + r_1^2}}\right) \cdot \dfrac{180}{\pi} & \text{otherwise} \end{cases}$$

Solar right ascension and declination are then converted to degrees, minutes, seconds format from the decimal degrees calculated.

C.15 Lunar Right Ascension and Declination

The following vector is required for the calculation:

$$\vec{R}_{GEI}(☾) = r_0 \cdot \hat{x} + r_1 \cdot \hat{y} + r_2 \cdot \hat{z}$$

where $\mathbf{R}_{GEI}(☾)$ is a three dimensional GEI vector in centimeters from the center of the earth to the center of the moon. This vector is calculated using the Jet Propulsion Laboratory (JPL) Export Ephemeris Package.

Calculate the right ascension (*ra*) as follows:

$$ra = \begin{cases} 0.0 & \text{for} \quad r_0 = r_1 = 0 \\ \tan^{-1}\left(\dfrac{r_1}{r_0}\right) \cdot \dfrac{180}{\pi} & \text{otherwise} \end{cases}$$

If *ra* is less than 0.0, add 360.0.

Calculate the declination (*dec*) as follows:

$$dec = \begin{cases} 0.0 & \text{for} \quad r_0 = r_1 = r_2 = 0 \\ \tan^{-1}\left(\dfrac{r_2}{\sqrt{r_0^2 + r_1^2}}\right) \cdot \dfrac{180}{\pi} & \text{otherwise} \end{cases}$$

Lunar right ascension and declination are then converted to degrees, minutes, seconds format from the decimal degrees calculated.

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Appendix D

COORDINATE TRANSFORMATIONS[9,11-13]

D.1 GEI To GEO

Let the angle from the X-axis of GEI to the Greenwich meridian measured eastward in the Earth's equator be θ. The angle θ is referred to as the Greenwich Mean Sidereal Time.
The transfer from GEO to GEI is

$$\begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix}_{GEI} = \begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix}_{GEO}$$

or

$$\vec{U}_{GEO} = [(\cos\theta)\cdot V_x + (\sin\theta)\cdot V_y]\,\hat{x} + [(-\sin\theta)\cdot V_x + (\cos\theta)\cdot V_y]\,\hat{y} + [V_z]\,\hat{z}$$

and the inverse transformation is

$$\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix}_{GEO} = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix}_{GEI}$$

or

$$\vec{V}_{GEI} = [(\cos\theta)\cdot U_x + (\sin\theta)\cdot U_y]\,\hat{x} + [(-\sin\theta)\cdot U_x + (\cos\theta)\cdot U_y]\,\hat{y} + [U_z]\,\hat{z}$$

D.2 GEO To MAG

Let θ be the GEO colatitude and ϕ the GEO longitude of the centered dipole axis in its extension through the northern hemisphere of the earth. The transformation from GEO to MAG is

$$\begin{bmatrix} \cos\theta \bullet \cos\phi & \cos\theta \bullet \sin\phi & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \\ \sin\theta \bullet \cos\phi & \sin\theta \bullet \sin\phi & \cos\theta \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix}_{GEO} = \begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix}_{MAG}$$

or

$$\vec{V}_{MAG} = [(\cos\theta\cos\phi)\cdot V_x + (\cos\theta\sin\phi)\cdot V_y + (-\sin\theta)\cdot V_z]\,\hat{x} + [(-\sin\phi)\cdot V_x + (\cos\phi)\cdot V_y]\,\hat{y} + [(\sin\theta\cos\phi)\cdot V_x + (\sin\theta\sin\phi)\cdot V_y + (\cos\theta)\cdot V_z]\,\hat{z}$$

The parameters of the centered dipole model of the earth's magnetic field specified by the first three Gauss coefficients g_1^0, g_1^1, h_1^1. The formulas for determining colatitude and longitude of the intersection of the centered dipole axis with the northern hemisphere are

$$\theta = \cos^{-1}\left(\frac{-g_1^0}{\sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2}}\right)$$

and

$$\phi = \tan^{-1}\left(\frac{h_1^1}{g_1^1}\right)$$

The values of colatitude and longitude are found by substituting the International Geomagnetic Reference Field (IGRF) or the Definitive Geomagnetic Reference Field (DGRF) values of the Gauss coefficients for the desired year. These values can be found in Table 2 of reference 12 and Table 1 of reference 13.

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